MULTIDISCIPLINARY APPROACH TO SCALING OF SPECTRAL MODELS OF INTEGRAL AQUATIC COMMUNITIES

Yury Kamenir¹ and Boris Shteinman²

¹ Bar Ilan University, Department of Life Sciences Ramat Gan 52900, Israel

²Israel Oceanographic and Limnological Research, Kinneret Limnological Laboratory

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ABSTRACT

The aim of this study is to search for operational parameters for scaling of models of integral aquatic communities.

Comparative analysis performed using several aquatic ecosystems, taken from the maximal possible range of ecosystem sizes, shows the existence of scaling parameters applicable in formal quantitative models integrating the aquatic community and its inhabitancy parameters.

Selection of the modeling schemes (spectral analysis and nonlinear empirical equations), parameters and constraints is through a deductive approach starting from a minimal model describing the natural aquatic community as an integral dissipative structure. The main property of the model (Ideal Minimal Ecosystem, IMES) is its ability to exist withstanding changes in the environment, deficiencies in its composite organization and structure, and faults in its inner components. This ability (or functional stability) is implemented through continuous replacement of numerous "flow-through elements" (FELs), recycling a finite store of resources.

The optimal approaches for analysis of the structure and dynamics of such an object are statistical, including regression analysis and size spectra that are now common in hydrobiology and theoretical ecology.

The hierarchical structure of size spectra favors searches for similarities of very different time-space scales. The existence of known allometric equations provides opportunities for estimating the time scale of numerous important biotic processes from the size (or body weight) composition of the studied ensemble of organisms.

Lake Kinneret (Israel) is used as a study site to analyze the specific mechanisms of influence of the water mass on the structure of the biotic components of the lake ecosystem. Analysis of empirical data, obtained with the help of modern means of monitoring (dual-beam echosounder), is used to illustrate the schemes proposed and the problems of application of an ideal model and parameter interpretation at a definite (real) aquatic ecosystem.

1. INTRODUCTION

Scaling is currently widely applied in ecology, but mainly at the level of the organism. The existence of a large number of regression equations, relating many important properties of organisms of practically all the main taxonomic groups to their size (D) or body weight (W), (Peters 1983; Schmidt-Nielsen 1984) provides a powerful apparatus for flexible transformations of "ataxonomic" (Schwinghamer 1981; Steinberg et al. 1996) mathematical schemes describing integral communities. There are also numerous studies relating the statistical properties of communities (e.g. number of species) to the scale of the ecosystem (e.g. area of a lake or island) (MacArthur & Wilson 1967; Begon et al. 1986). Integration of these two branches could produce a powerful mathematical apparatus for modeling and forecasting, analogous to the methods known and widely used in other spheres of hydroecology, such as hydrodynamics.

Statistical comparative analysis of large numbers of taxonomic groups and natural aquatic communities has already revealed the existence of typical patterns (Schwinghamer 1981) of size structure of taxonomic groups of various levels (Chislenko 1981) and distribution functions (Size Spectra, SS) of the community biomass, surface, production, respiration, organism number, etc. (Sheldon et al. 1972; Kerr 1974; Sprules & Munawar 1986; Krupatkina et al. 1987; Kamenir & Khailov 1987; Thiebaux & Dickie 1993; Sprules & Goyke 1994; Lopukhin & Kamenir 1995; Kamenir & Shteinman 1998).

Rapid developments in technical methods and computer programs, providing opportunities for measurement of parameters for huge assemblages of cells and aquatic organisms (particle counters, cell selectors, flow cytometry, microcalorimetry and respirometry) and statistical processing, have created a sufficiently new situation for the information support (Yentsch et al. 1983) of statistical models describing aquatic communities.

The main aim of this study is a search for scaling schemes, parameters and constraints for transformation of mathematical models describing integral self-regulating communities, for ecological forecasting of the future structure and dynamics of the community, based on application of the model scaling.

2. THE APPROACH

A search for methods and schemes for ecological forecasting of the future structure and dynamics of natural communities and ecosystems is performed here via the deductive approach starting from a minimal model of the object, considered as a whole (Kamenir 1983, 1986; Kamenir & Shteinman 1998).

2.1 The model

The model, the Ideal Minimal Ecosystem (IMES), is a closed volume (buffer) protecting a closed recycling flow which implements the quasi-cyclic process of renewal of flowthrough elements (FELs) of the same structure (Fig. 1).



Fig. 1. Ideal Minimal Ecosystem (IMES). lin, lout, Ic - in-, out-, recycling flow, respective.

The main property of IMES is its ability to exist, i.e. to maintain its principal functional characteristics, withstanding changes in the environment, deficiencies of its composite materials, structure and subsystems, and faults in its inner components. This ability (or functional stability) is implemented through continuous replacement of numerous flow-through elements of the same (i.e. hierarchic) structure, a self-stabilizing process maintained within a closed envelope (membrane) protecting a volume of inner medium.

All FELs go through an ontogeny cycle: growth, development, search for a vacant place in the system, adaptation to it, and changing efficiency of functioning; offspring production; aging of inner substrates, structures and algorithms; growing problems of self-maintenance or stabilization, incapability to counteract some changes of inner substrates or surrounding environment.

As each function of IMES is performed by a multitude of FELs, inclusion/exclusion of some components, even a large proportion of them, is not crucial for the system as a whole. The real problem is in obtaining resources for the production of new FELs, i.e. successors to the former ones. A very important property of the system is its use of complete resource regeneration which solves both the problem of resources for production of new FELs and the problem with the "burial" of the former ones (Kamenir 1983).

2.2. Ideal Object

As IMES is an ideal model, it depicts not real complications but a minimal set of interrelated problems and solutions of principal importance.

The most important features of IMES (Fig. 1) are:

1. implementation of the whole system based on flow-through elements;

2. use of recycling as a means of resource supply and pollution prevention;

3. realization of each function of self-maintenance by a high number of FELs;

4. realization of each function by a heterogeneous ensemble of FELs going through sufficiently different stages of the ontogeny cycle;

5. stabilization of its inner medium via the use of membranes, i.e. active control of the border-layers and border-crossing fluxes;

6. use of the feed-back, an intrinsic property of a closed loop;

7. use of resonance, a highly effective mechanism of selective stabilization of timespace scales, intrinsic to a closed membrane and closed loops;

use of a hierarchic structure of FELs (elements, membranes, processes);

9. use of a broad spectrum of time-delays through the hierarchic branching of the closed loops, as an effective means of feed-back stabilization (Kamenir 1986, 1987).

The IMES model is minimal in the number of elements and parameters applied to describe the principal properties. It is ideal, i.e. does not describe a real object but rather an asymptotic state, such as the absolute zero (-273°C) temperature, an ideal gas, a point (a zero-volume object), a straight line, *perpetuum mobile*, etc.

A real system may move towards such a state, but can never achieve it, due to the existence of other laws of nature, not considered in a *minimal* model. However, the existence of a known asymptotic value (point, line) can be used for the development of a system of coordinates, measureof distances, comparisons of real objects and quantitative analyses of differences and displacements within the coordinate space; i.e. it can be used for quantitative description of the system state, progress and evolution.

Selecting the self-maintaining recycling movement as the main property of the object, we see a hierarchy of closed membranes, recycling fluxes and flow-through elements (Figs. 1 and 2).

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Fig. 2. Transformation of the trophic net (a) to a cascade of correlated recycling fluxes (b, c). Ip - primary production, i.e. energy input.

There are a number of models, described in recent times by other authors, which consider the importance of the many peculiarities of IMES: continuous flow-through movement (Cuvier 1827), recycling (Finn 1980; May 1981; Patten 1985), feed - back loops (Stone & Berman 1993), hierarchy of cyclic blocks and processes (Lotka 1925), and distributed ensembles of a huge number of *molecules* of a gas-like *living matter* (Vernadsky 1929, 1978).

In this manner, IMES depicts not only a hierarchical structure of natural ecological systems but also the biosphere as a whole, the highest level ecosystem of the earth (Odum 1971), and the intracellular cyclic nets of the metabolic reactions. As such it tries to integrate concepts of biogeochemical cycling, the *living matter* of V. Vernadsky (1929, 1978) and the *Tourbillon Vital* of G. Cuvier (1827).

IMES also resembles a broad class of objects studied in recent times by a rapidly developing branch of science, the thermodynamics of irreversible processes or the theory of dissipative processes. The optimal approaches for analysis of the structure and dynamics of such an object are statistical (Nicolis & Prigogine 1989).

2.3. Biological Coherent Dissipative Structure

The dissipative structures theory can provide a possible mode of synthesis of such an aquatic ecology model with models used in hydrodynamics. We make it via the introduction of the notion of the Biological Coherent Dissipative Structure (BCDS) (Kamenir & Shteinman 1998), for a comparison of the IMES-model with the ideas and notions of the theory of Dissipative Structures (DS):

1. The term biologic is quite reasonable here, as every aquatic community is a biological object, composed of living organisms and studied by the science of biology.

2. It can be considered as a system, i.e. "a regularly interacting or interdependent group of items forming a unified whole" (Webster 1961), a whole that has new (emergent) intrinsic properties inherent to none of the items which compose the whole. Some of these properties of the whole (e.g. the energy dissipation spectra, the distribution functions of the elements) are to be analyzed with the help of special, statistical methods describing not single elements, but ensembles. In this case the parameters' estimate of mathematical approximations of such spectra (e.g. temperature) characterize the state of the system, not the state of some of the elements in the system (Nicolis & Prigogine 1989).

3. An ecological system is a dissipative structure, as it has all the main DS characteristics:

- it is far from equilibrium and exists only due to a continuous flow of energy;

- its emergence and destruction can be seen through changes between chaos and correlated processes and ordered structures;

- some of the characteristics of these structures (e.g. distribution functions) depict only the macroscopic object, and not some its elements;

- the ecosystem adapts itself to the surrounding environment and can have several different states and means of adaptation (Odum 1971).

4. An ecosystem is a coherent structure, i.e. it consists of parts that "hold together firmly as parts of the same mass" (Webster 1961), of processes that are inter-dependent and correlated. A very important IMES property is the necessity of correlation (both amplitudes and phases) of a number of periodic processes and recycling fluxes providing many different resources for the production of a multitude of new FELs.

2.4. Living Vortex

The most important properties, needed "to form the just idea of the nature of life", were selected and described some two centuries ago by the great French biologist G. Cuvier. Life (according to his definitions) is a vortex, the action of which is constant, all particles are in a state of perpetual mutation, constantly coming and going. Life consists of *combinations*, existing, for a time, in one determined form, by continuously attracting particles of extraneous substances from without, and by returning their own particles to

the surroundings. The system is living only while this movement continues; this "vital motion" prevents the system dissolution due to the chemical affinities of the chemical elements composing it. To become mixed and penetrate the body, all the elements are actually identified with the fluent liquid. The movement of liquids is possible only due to the existence of the organization of a variety of arrangements or necessary conditions. A change in any of those conditions or partial movements, of which the totality is composed, inevitably leads to cessation of life (Cuvier 1827).

Therefore, the main property of BCDS (i.e. the incessant, self-maintaining movement of flow-through elements) was long ago noted as a fundamental property of living systems.

2.5. Hydrodynamic Cascade

Application of the Living Matter concept supports and complements the IMES-model. An integral object, used instead of a set of interacting taxonomic units, helps overcome many difficulties that are found in the most common taxonomic simulations (Odum 1971; Holling 1978) and food web models (Patten 1985; Higashi et al. 1992).

A set of moving resource-pools (e.g. micro- and macro-nutrients) is realized in the form of a stable set of interdependent recycling fluxes or quasi-cyclic processes, correlated both in their amplitudes and phases. The model, concentrating on the structure and stability of the recycling flux cascade (Fig. 2), seems to be suitable for comparison with hydrodynamics models. The BCDS (Kamenir & Shteinman 1998) notion was used to search for a means of adaptation of the hydrodynamics methods.

It seems that the ideal object (model) considered above provides both a theoretical and methodological means for adaptation of scaling (a method which has been very successfully used for a long period of time in hydrodynamics) to ecological modeling. A very important structure existing within the aquatic ecosystem is an ensemble of correlated, interdependent recycling fluxes of the main resources, embracing a large interval of time-space scales, and existing much longer than the "particles" that compose the whole vortex (Odum 1971; Kamenir 1983; Kamenir & Shteinman 1998).

The above DS properties uniting both the hydrodynamic cascade and the living cascade (BCDS), show a major similarity between these two systems, and also the applicability of the dissipative structures theory and methodology for the study of both cascades (Fig. 3).

Not only are the organizing role and dissipation of the energy flow important properties of both systems, but there are also the cascade of recycling vortexes, the broad timespace range, broad frequency spectra, correlation of many sub-processes and partial movements, the coming and going of small particles and elements, etc. Even adaptation to the external environment (a fundamental property of living systems) is mentioned for DS and is a typical feature of many hydrodynamic objects, e.g. river-bed processes (Shteinman 1985, 1988).

An additional property, inherent to both objects, is the existence of chaotic components created in the course of transformation of external impacts, interfering with the stable structural elements, and unable (as a rule) to destroy their correlated functioning (Grinvald & Nikora 1988).

The principle of minimum energy dissipation is common to hydrodynamic systems: a water flow so organizes (adapts) its movement and structure that the energy dissipation is minimal (Velikanov 1955). An analogous principle is true for biological systems that eliminate unnecessary elements and optimize the structure and functioning of the subsystems left, in such a way that the energy dissipation is minimal (Libbert et al. 1980). This helps in the search for minimal models of biological objects, concentrating on a small number of the most important structural elements, propertieand processes.



Fig. 3. Energy dissipation spectrum of sun light (a), terrestrial (b) and the World ocean (c) biotic communities; from Gorshkov (1982) and Kamenir (1987).

3. ANALYSIS OF BCDS

As the above BCDS properties show for the application of spectral methods, hydrodynamic experiences could be very valuable and should be considered. Approaches of this type (Size Spectra and non-linear regression equations) have been used and developed in biology, and especially in aquatic ecology, for several decades (Sheldon et al. 1972; Schwinghamer 1981; Peters 1983; Sprules & Munawar 1986; Sprules & Goyke 1994; Holling 1992). However, the studies are mainly devoted to the distribution of the mass of living organisms; most of the papers just describe empirical data. Nevertheless, a growing number of the objects described has led to comparative studies, which have shown the existence of many scaling transformations (regression equations) (Hemmingsen 1960; Peters 1983) and typical patterns (Schwinghamer 1981) of ecological spectra.

3.1. Scaling

Scaling has been applied in biology for a long time at the level of the organism (Schmidt-Nielsen 1984). The influence of the ecosystem size on parameters of taxonomic composition (a specific biological description of the community structure) was the subject of many studies in biogeography (Begon et al. 1986). Comparison of the energetics of ecosystem development in systems of sufficiently different time-space scales (Fig. 4) reveals a means to scale some processes and integral indexes of self-maintaining communities.



Fig. 4. Dynamics of the communities of considerably different time-space scales (Odum 1971, with changes). B - biomass, $P_{N_i} P_{G_i} R$ - energy flows. Forest (time = years) and microbial (time = days) community succession.

Direct projection from the laboratory microecosystems to a large-scale natural ecosystem may not be entirely valid. However, some basic trends are characteristic of development on land, in large bodies of water and in small laboratory microecosystems (Odum 1971).

3.2. Typical Patterns

Studies from the last century have shown regularities of a very general nature concerned with the probability distributions of living, dead and inorganic matter. Size Spectra (SS) of various natural communities, e.g. plankton, benthos, fish, microorganisms, etc. of various marine and freshwater basins are among the most interesting regularities.

Recently, the existence of "typical patterns" (Schwinghamer 1981) was shown for the size structure of various natural communities of terrestrial, marine and freshwater ecosystems, including streams and lakes (Sheldon et al. 1972; Chislenko 1981; Schwinghamer 1981; Gorshkov 1982; Peters 1983; Krupatkina et al. 1987; Lopukhin et al. 1990; Kamenir 1991a; Sprules & Munawar 1986; Sprules & Goyke 1994; Witek 1995). "Typical estimates" of integral community parameters are produced and maintained by the force of "nonnutrient constraints" existing in natural aquatic ecosystems (Agusty et al. 1992; Kamenir 1992). The application of such typical estimates and patterns can help us to save time and human resources, and obtain a compact data set describing the state and structure of integral natural communities, up to the largest ecological systems of the Earth (Kamenir 1987), with the help of quite reasonable resources over a reasonable timeframe.

3.3. The Size Spectrum Evolution Criterion

Mathematical analysis of the properties of the BCDS model produced a scheme of evolution of the integral self-sustainable community Size Spectrum (SS) in the course of succession and regression. According to such a scheme, succession of the ecosystem manifests itself by broadening the size spectrum of the living matter. Degradation, e.g. under environmental stress or anthropogenic influence (pollution, eutrophication, overfishing), produces the opposite trend (Fig. 5).





The SS change is aimed at stability of the closed recycling fluxes, and the integral parameters described later.

Particularly significant are changes on the right side of the spectrum. Its extreme right point, i.e. size or body weight of the largest organisms of the community (Wm), is a very informative indicator of the ecosystem state. This spectrum breadth criterion was obtained (Kamenir 1986, 1991b; Kamenir & Shteinman 1998) on the basis of mathematical analysis of the stability of closed feed-back loops (Iljichev 1982), which are an important part of the IMES structure as discussed above.

The existence of known allometric equations (Peters 1983) provides opportunities for estimating the time scale of numerous important biotic processes from the size (or body weight) composition of the studied ensemble of organisms. The hierarchical structure of IMES, and the hierarchical organization of size spectra (Chislenko 1981; Kamenir 1986) support the search for similarities of very different time-space scales (Kamenir 1991b).

The hierarchic structure of the object (IMES) may lead to a similarity in both the spatial and temporal structure of sub-models of sufficiently different time-space scales. This provides an opportunity to see "the future in the past", i.e. document the dynamics of the studied object through experiment (passive or active) on another object of a sufficiently smaller scale (Kamenir 1991b; Kamenir & Shteinman 1998).

Because one can extrapolate from processes that take much less time, the study uses much less resources, and can be performed on much less precious or unique objects.

3.4. A Search for Typical Patterns and Estimates

A literature-based analysis was performed (Kamenir & Khailov 1987; Kamenir 1991a; Kamenir & Shteinman 1998) on the development of the application of scaling methods to biotic component modeling. The following criteria were used for the selection of the references: analysis of all ecosystem size intervals possible for this planet, comparison of natural and artificial, of marine and freshwater communities, of laboratory measurements and field studies data.

An optimal set could be composed of the world ocean, a sea, a lake, a reservoir, a pond, a mesocosm, a microcosm and a microbial vial. A series of thoroughly studied objects of aquatic ecology was compiled (Table 1) from the available literature.

Table 1. Parameters of integral aquatic communities

(Kamenir & Shteinman 1998)

Eco-	Geometrical dimensions of the systems			I I	Per unit area (m^2)		Largest
system					community parameters organism body		
	Volume	Area	Depth		Biomass	Surface	weight
	Ve, m^3	Ses, m^2	h, m		B2, kcal	ISI, m^2	Wm, pg
1 World ocean	1.40E+18	3.60E+14	3.70E+03		7.34E+01	9.84E+01	1.00E+20
2 Black sea	5.40E+14	4.20E+11	1.30E+03		7.77E+01	1.35E+02	6.00E+17
3 Rybinsk res.	2.50E+10	4.60E+09	5.60E+00		7.06E+01	2.50E+02	2.00E+15
4 Lake Drivyaty	2.00E+08	3.30E+07	5.90E+00		2.00E+02	3.45E+02	3.00E+15
5 Outdoor pond	1.70E+01	6.57E+01	3.00E-01		1.00E+02	1.48E+02	2.90E+11
6 Indoor pool	2.00E-01	4.00E-01	5.00E-01		3.93E+01	6.13E+01	1.70E+11
7 Microbial com	5.00E-04	1.00E-02	5.00E-02		4.11E+01	2.08E+02	1.50E+04
8 Microb. vial	5.00E-05	2.50E-03	2.00E-02		6.79E+00	3.63E+01	1.00E+03

Parameters calculated per unit area

Well-known experimental studies, with sufficiently complete data (encompassing all fractions of living matter), were selected. Of several experiments of the same type those most conforming to the model (BCDS) were chosen, i.e. self-maintaining, closed, balanced systems with minimum nutrient addition and other impacts. The values obtained at the end of the experimental period were used. To have a reasonably small data set (Table 1), eight systems were used; analysis of additional publications did not provide important corrections of the results discussed. A formal quantitative parameter Size Fraction (SF) was added to the original data to develop size spectra.

Typical patterns of those spectra and the suitability of those patterns for communities of the highest rank and scale are very interesting, these include SS of the living matter of integral seas, the world ocean and the whole Biosphere (Sheldon et al. 1972; Chislenko 1981; Gorshkov 1982; Peters 1983; Kamenir & Khailov 1987; Lopukhin et al. 1990; Witek 1995; Jonash & Fournier 1998). Other important regularities are the SS (granulometry) of sediments (Wentworth 1931) and of many other environmental parameters, e.g. see a data set comparison in Kamenir (1987). Numerous allometric equations, i.e. nonlinear statistical correlations (Hemmingsen 1960; Peters 1983), provide a formal quantitative apparatus for transformations of SS.

Hydrodynamics experience shows that such transformations allow us to calculate, on the basis of the spectra, a number of very valuable integral estimates.

Parameters and description of schemes based on formal quantitative, well adapted for use of computerized instruments (operational) concepts of living matter, provide opportunities for the application of automated technical means of parameter measurement and monitoring, e.g. adenosine triphosphate (ATP) measuring devices, microcalorimetry, flow cytometry, cell selectors, echo-sounders, etc (Yentsch et al. 1983; Kamenir 1986; Lopukhin et al. 1990; MacLennan & Simmonds 1992; .Lopukhin & Kamenir 1995).

3.5. Parameters of State

The parameters for description of the state of the system (biotic component of the water body) were chosen on the basis of the model used (BCDS). Closure of the main fluxes of the model implies that the energy influx is the main limiting factor, as its recycling coefficient is much lower than the nutrient coefficient. As the energy (sunlight) flux (compensating the recycling losses) has dimensional, L^{-2} (e.g. W m⁻²), the living matter (i.e. the totality of living beings inhabiting a unit area or the whole water area) is the constraint object, rather than a species or a unit volume of inhabitants. Description of the living matter implies that the SS width is large and important (Kamenir 1986), hence the extreme points of the SS, i.e. the body weights of the smallest and the largest organisms (Wx, Wm) are of special interest. While study of Wx is very difficult, analysis of Wm is possible.

When the size spectrum width is large [log(Wm/Wx) >> 1)], as in many natural communities, one cannot neglect the differences in specific energy requirements of organisms of various size. The biomass (B) overemphasizes the importance of large organisms, and numbers (N) overemphasize the importance of small ones (Odum 1971). A power function (log Y ~ b log W, b ~ 0.75-0.80) describes this disproportion (Peters 1983). The "metabolic surface" (Sm; lungs, gills, etc.) equation has a similar power coefficient b ~ 0.78 (Kamenir & Khailov 1987; Khailov & Kamenir 1998; Lebedev et al.

1989); hence, Sm is preferable to N and B when one depicts the energy dissipation according to the model (BCDS) used.

3.6. Data Processing:

The methods of size spectra calculation and plotting are as described by Sheldon et al. (1972), Schwinghamer (1981) and Chislenko (1981). All organisms were distributed into size fractions (Sieburth et al. 1978) according to their size D given by the authors or obtained from the cell volume (V), weight (W) or the biomass (B) and number of organisms (N) given: log D ~ 0.33 log V, where V = W/ ρ , W = B/N, ρ ~ 1 g cm⁻³; size fractions are standard increments of the organism size logarithm [log (D₂/D₁) = 1].

The size fraction number corresponds to its left border, i.e. its minimum size D_i

 $(i = \log D_i, \mu m).$

The external or "geometric" surface of organisms was calculated using the "equivalent spherical diameter": St = 3.14 ESD^2 , where the ESD for each SF was the mean size, i.e. the geometrical mean of D_i and 10 D_i. The allometric coefficient, accounting for the difference in the surface values of the natural organism with highly developed morpha (Sm) and of the sphere of the same volume (Sg) (Khailov & Kamenir 1988), was used then: Sm = St KSS. Summing up with regard to the Sm of all organisms within all fractions, we obtain the size spectrum of the metabolic surface; the sum of all fractions per m² of the water area gives the Integral Surface Index (ISI, m² m⁻²), a dimensionless parameter. The sum of all St gives the "geometric surface" (Sg) size spectrum and integral value.

3.7. Results

The estimates derived (B2, ISI), supplemented with the geometrical dimensions of the systems (water body volume Ve, its area Ses, mean depth h) and the body weight of the largest organism of the community (Wm), produced the resulting description set (Table 1) (Kamenir & Shteinman 1998).

A change in a number of parameters of the water body and its biotic community with the object scale (its water area size, Ses) is presented in Fig. 6.



Logarithms of parameters

Fig. 6. Influence of size (area) of an aquatic ecosystem on its morphometric and biological parameters, from Kamenir & Shteinman (1998); symbols are explained in the text.

4. DISCUSSION

A set of water bodies of various scales (water area Ses range about 20 orders of magnitude) and parameters of description of their biotic component state (the integral mass of living organisms (Bsum), surface of their bodies (Sm), maximal weight of the "living matter particle" (Wm), normalized to the water area indexes, B2 = Bsum/Ses, ISI = Sm/Ses) was designed with the help of a minimal model of the object (BCDS). Comparison of the data obtained from the set of water bodies indicates linear growth, with the system scale (water body area), of integral parameters of the community (the biomass and surface of bodies of all organisms; Fig. 6, curves Bsum and Ssum, respectively). When normalized to the water area size, these parameters (curves B2 and ISI) seem to be relatively constant for ecosystems of various sizes. Indexes of the total biomass (B2) for these systems are near 100 kcal m⁻²; indexes of total surface of all organisms are about 20-200 m² m⁻² (i.e. dimension-less). These values are close to estimates that we described previously for another set of ecosystems (Kamenir 1991a). Size spectrum descriptions of the aquatic communities of Lakes Superior and Michigan, Scotian Shelf, Bay of Fundy and Brown Banks, including both pelagic and benthic parts (Boudreau & Dickie 1992), show about the same biomass estimate (log B2 ~ 2, i.e. B2 ~ 100) and size distribution. A similar estimate (100 g wet weight) was discussed previously (Schwinghamer 1981) as typical for natural aquatic systems.

These results agree well with our estimates of the microbial biomass per unit area of the Earth (Ac, mg ATP m⁻²), obtained earlier through bibliographic data survey and cruise works: log Ac = 1.16 ± 0.55 , i.e. some 4 g carbon of microorganisms (i.e. organisms smaller than 100 um; about half width of the integral living matter SS) per m² (Kamenir et al. 1986; Lopukhin et al. 1990). A close estimate (some 4.5 gC) for integral marine planktonic communities was obtained from an extensive screening of works, published over the past 20 years in major journals on the area, done by Gasol et al. (1997, Table 1, summing the means for auto- and heterotrophs).

Another index distinctive of low variability, i.e. integral community destruction (energy flow) per unit area of ecosystem, was discussed by Odum (1971). The right extremity of the community size spectrum, i.e. the largest organism weight (Wm) also shows an approximately linear relationship with the water body area (Fig. 6).

The size spectra have a pattern similar to those already described in the literature, i.e. several "domes" or "bells", using the terms of Bodreau & Dickie (1992) and Sprules & Goyke (1994). The spectra are composed of bells of about the same order of magnitude, more or less symmetrical in the logarithmic scale of the X-axis, with gaps between them. The amplitudes and positions of the bells are different for different communities.

We think that the results obtained support the idea of the comparatively low variability

of SS patterns and of some indices of integral aquatic communities, calculated per unit area (these are the living matter (B2) and metabolic surface index (ISI)). Of the parameters chosen only Wm varies considerably with changes in the ecosystem size. Wm (a volumetric parameter) also correlates better with the water body area than with its volume or depth (Fig. 6).

There are two "ideal objects" (points 1 and 8) on Fig 6. These systems conform most to the ideal system (BCDS) definition (i.e. closed volumes, with minimal human impact and material exchange with surrounding space): a sealed microbial ampoule and the World ocean. One can see that almost all points in Fig. 6 lie quite close to the line connecting points 1 and 8 and almost all of the points are above this line.

A possible explanation, consistent with the BCDS concept described above, is that not all organisms present in the original data sets (i.e. inside the ecosystem), especially in artificial, experimental systems, are members of a self-sufficient community. Some would become extinct were the systems to be sealed. For example, *Artemia salina* Linn, in a Roux flask, dies (Fig. 6, point 7) 50 days after sealing of the system (Nixon 1969); hence, the point corresponding to this system should be moved closer to the line connecting points 1 and 8. The same changes were seen for systems 5 and 6 by Whittaker (1961).

The difficulties inherent in the problem of Wm estimation (the data collection and interpretation) were considered (Kamenir et al. 1998), using a study of the Lake Kinneret (Serruya 1978; Walline et al. 1993) size spectrum as an example (Fig. 7).



Fig. 7. Size spectrum of the Lake Kinneret fish community; a, b - modal and maximal body weight, respective; from Kamenir et al. 1998.

Dramatic changes in the annual and seasonal development of phytoplankton were

registered in Lake Kinneret since 1994. Berman &. Shteinman (1998) have utilized data from a recently developed 3-D velocity fluctuation meter to compute the dissipation of turbulent kinetic energies (TKE) and the intensity of turbulent mixing in horizontal and vertical planes in the pelagic, epilimnic water of Lake Kinneret in 1992 - 1996. The first appearance of the filamentous cyanobacterium Aphanizomenon in the lake in 1994 coincided with a period of markedly lower rates of TKE dispersion and a shift from vertical to horizontal dominance of the turbulent eddy spins. The absence of a regular winter-spring bloom of the dinoflagellate, Peridinium in 1996 occurred when dissipation rates of TKE were extremely high; record-high amounts of dinoflagellates (1994, 1995) appeared when dissipation rates were very low. Correlations were shown between phytoplankton parameters (chlorophyll, primary production, the ratio of primary production to chlorophyll) and both the dissipation rate of TKE and intensity of water turbulent mixing in the vertical plane (Berman & Shteinman 1998). As the phytoplankton groups listed above have sufficiently different cell volumes, these hydrodynamic changes were reflected in remarkable changes of the lake biomass SS. Nevertheless, the SS typical pattern and discussed above integral community parameters did not change significantly.

It can, therefore, be seen that analysis of bibliographic sources and field measurements data produced additional support for the existence of rather stable typical patterns of biomass and energy dissipation spectra of some ecological structures. Some similarities between patterns of hydrodynamic and BCDS spectra have also been shown. The general structure of the energy dissipation spectra (Fig. 3) of dissipative structures (negative power low approximation; the existence of several modal zones, more or less symmetrical on a logarithmic time scale) and of the object (cascade of recycling fluxes) producing these spectra show that some methods, developed in hydrodynamics and other fields of DS studies, may be applied in analysis of the biotic component of natural water bodies. As the spectra patterns hold for water bodies of considerably different scales, it is possible to draw on hydrodynamic methods of scaling to analyze the structure and functioning of large-scale aquatic ecosystems.

5. CONCLUSION

1. Application of methods, developed by hydrodynamics and other fields of science studying dissipative structures, can provide good methodology, recommendations and mathematical tools for:

description of the object considered as a whole; analysis of a statistical ensemble with the help of distribution functions and integral characteristics; selection of dimensionless parameters; search for constant estimates obtained from combinations of such parameters; search for logical models using such distributions and constants; search for mechanisms generating them.

2. Spectral analysis of the living matter structure, applied on the basis of such an approach, gave additional support for the existence of typical patterns of size spectra of integral aquatic communities; it provided tools for analysis of the typical pattern changes to be expected due to the change in the water body scale.

3. Analysis of a broad range of aquatic ecosystems, performed with the help of the BCDS model, shows that for a large range of ecosystem sizes (Ses), there are parameters that change approximately linearly with the ecosystem size. An index of this type is the body weight (Wm) of the largest species. Integral community biomass and surface, and community destruction also grow approximately linearly with ecosystem size, so that t hese parameters, when averaged over the annual cycle period and normalized to the ecosystem size, are nearly constant for various ecosystem sizes.

4. Such trends in changes in the parameters reveal the potential efficiency of scaling methods for aquatic ecosystem modeling on the basis of the integral parameters of the systems state.

Scaling, on the basis of typical patterns and the above-mentioned indices, can be an effective tool which is necessary for the development of forecasting methods in aquatic ecology.

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